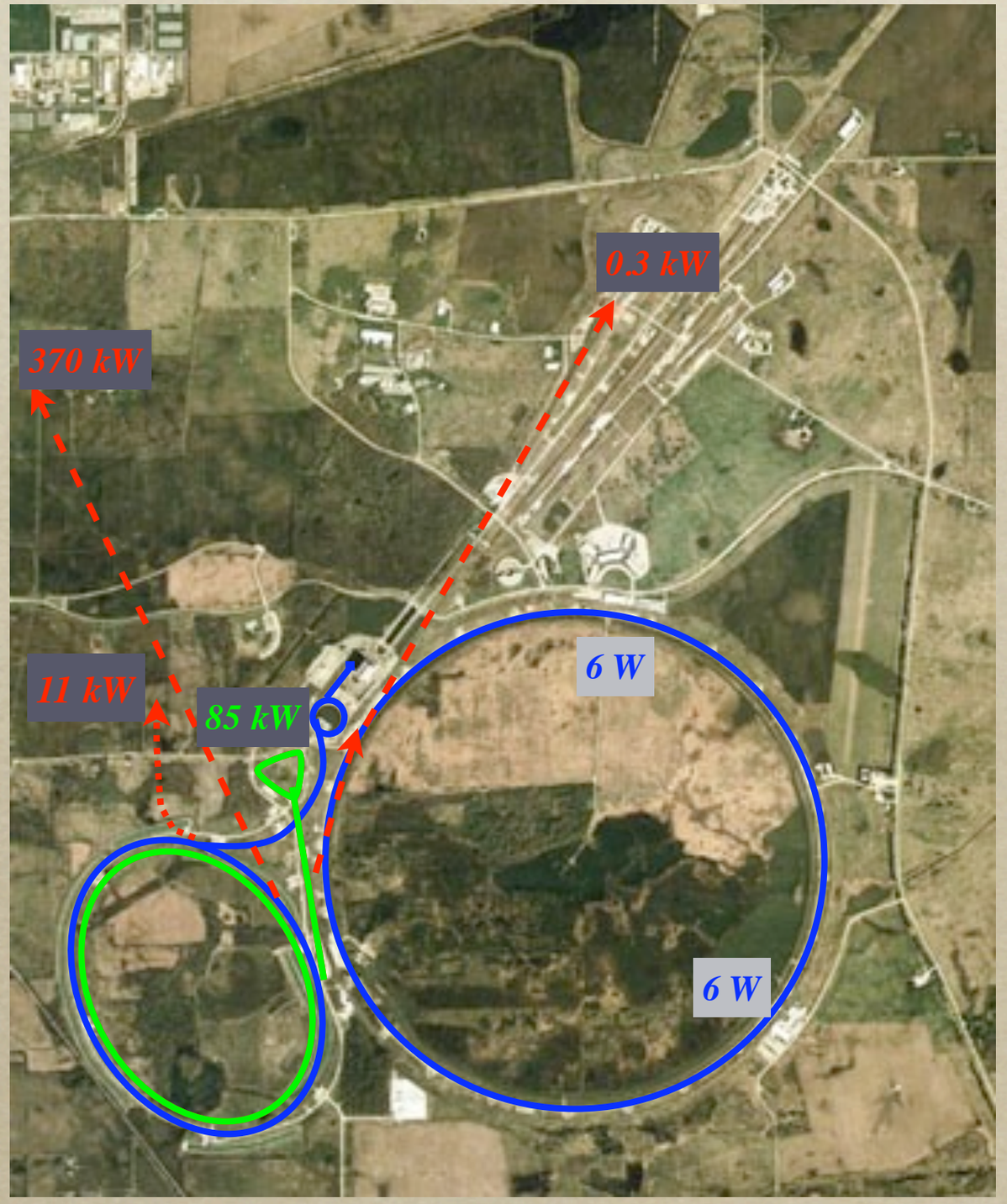
Accelerator Preparations for Future Fixed Target Experiments at Fermilab

Mike Syphers
Fermilab

- *Outline:*
  - *Overview*
  - *Main Injector Neutrino Program*
  - *Booster Program*
  - *Tev150 Stretcher Ring*

Run II Proton Availability

- *Daily Operation*
  - *Set up p-pbar store in Tevatron, ...*
  - *Produce more antiprotons, and drive the **neutrino** program*
    - *time line governed by 15 Hz Booster operation*
  - *11 Booster pulses to MI every 2.2 s*
    - *9 for NuMI*
    - *2 for pbar production*
  - *Off-load pbars to Recycler ~every hour*
  - *Spare pulses (~4) to miniBooNE*
  - *1 pulse to SY120 occasionally...*



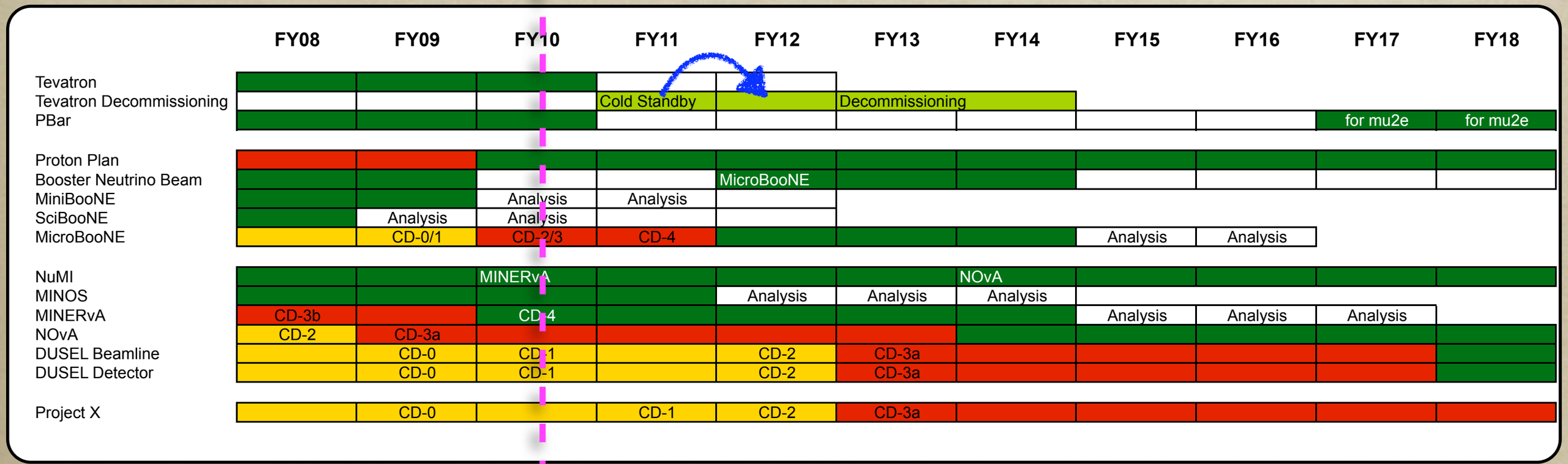
MJS / Fermilab

Neutrinos from the Main Injector

- *Ongoing program of long-baseline neutrino experiments*
  - *MINOS*
  - *MINERvA*
  - *NOvA*
  - *LBNE (future)*

Time Line of Events

- *Tevatron potentially will be decommissioned ~ 2011-14*
- *Neutrino program will be on-going into the far future*
- *Project X will be commissioned ~ 2020, if things "go well"*

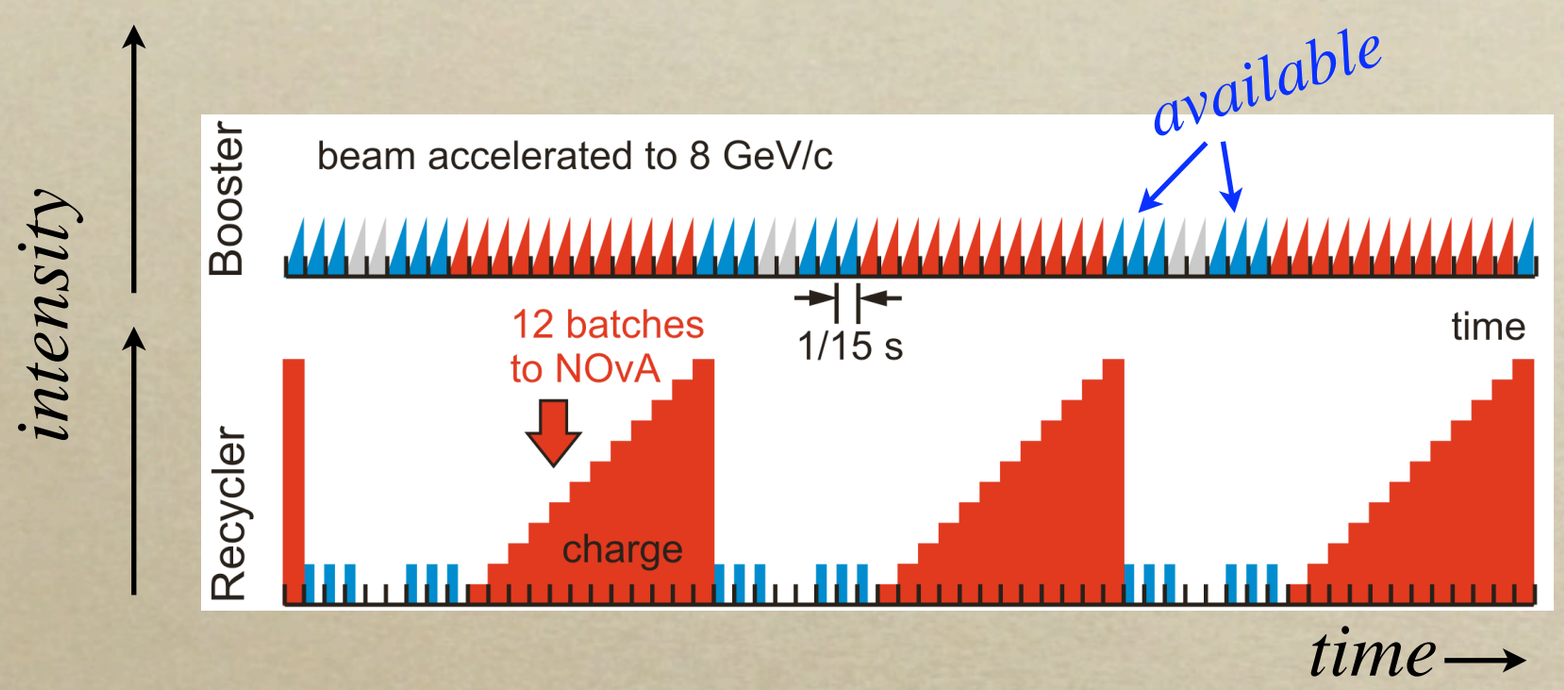


- *Meanwhile…*

MJS / Fermilab

NuMI/NOvA, after Run II

- *Following Run II, the NOvA experiment will ultimately use up to 12 Booster cycles per MI cycle*



ave rate of BOO
= 12/20*15 Hz
= 9 Hz

- *20 15-Hz Booster cycles (1.333 sec) per NOvA cycle*
- *Booster has been upgraded to perform at this level; if can run "flat out" at 15 Hz, leaves up to 8 Booster cycles for "other program(s)"*

Continued Booster upgrade program being performed to achieve full 15 Hz operation

Booster 8 GeV Program

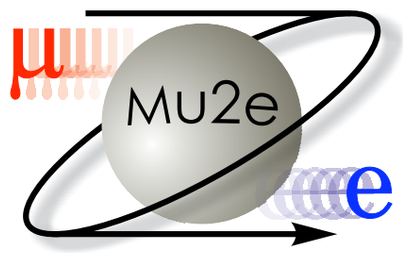
- *Spare Booster cycles in time line allow for...*
  - *Booster Neutrino Beam (BNB)*
    - *miniBooNE* *(nearing completion)*
    - *microBooNE* *(CD-0 approval; CD-1 review next month)*
  - *Muon-to-Electron Conversion (Mu2e)* *(CD-0 approval)*
  - *Muon g-2 Experiment; EDM experiment (?)*
  - *Targeting R&D*
  - *Future ... Kaon program, muCool, etc., ...*

8 GeV Beam Proposals

- *To date, two experimental collaborations have submitted proposals to Fermilab PAC:*
  - ***Mu2e*** *has been given "Stage I Approval" from the lab, and CD-0 from DOE*
  - ***New g-2*** *is still under consideration*
    - *Presented twice to the Fermilab PAC*
    - *PAC recommends, "if funding available"*

Proposal to Search for $\mu^- N \rightarrow e^- N$ with a Single Event Sensitivity Below 10^{-16}

Mu2e Experiment



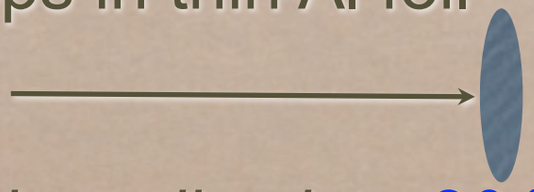
The New $(g-2)$ Experiment:

A Proposal to Measure the Muon Anomalous Magnetic Moment to ± 0.14 ppm Precision

New $(g-2)$ Collaboration: R.M. Carey[1], K.R. Lynch[1], J.P. Miller[1],

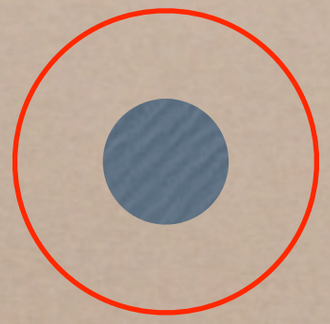
Mu2e

μ^- stops in thin Al foil



the Bohr radius is ~ 20 fm, so the μ^- sees the nucleus

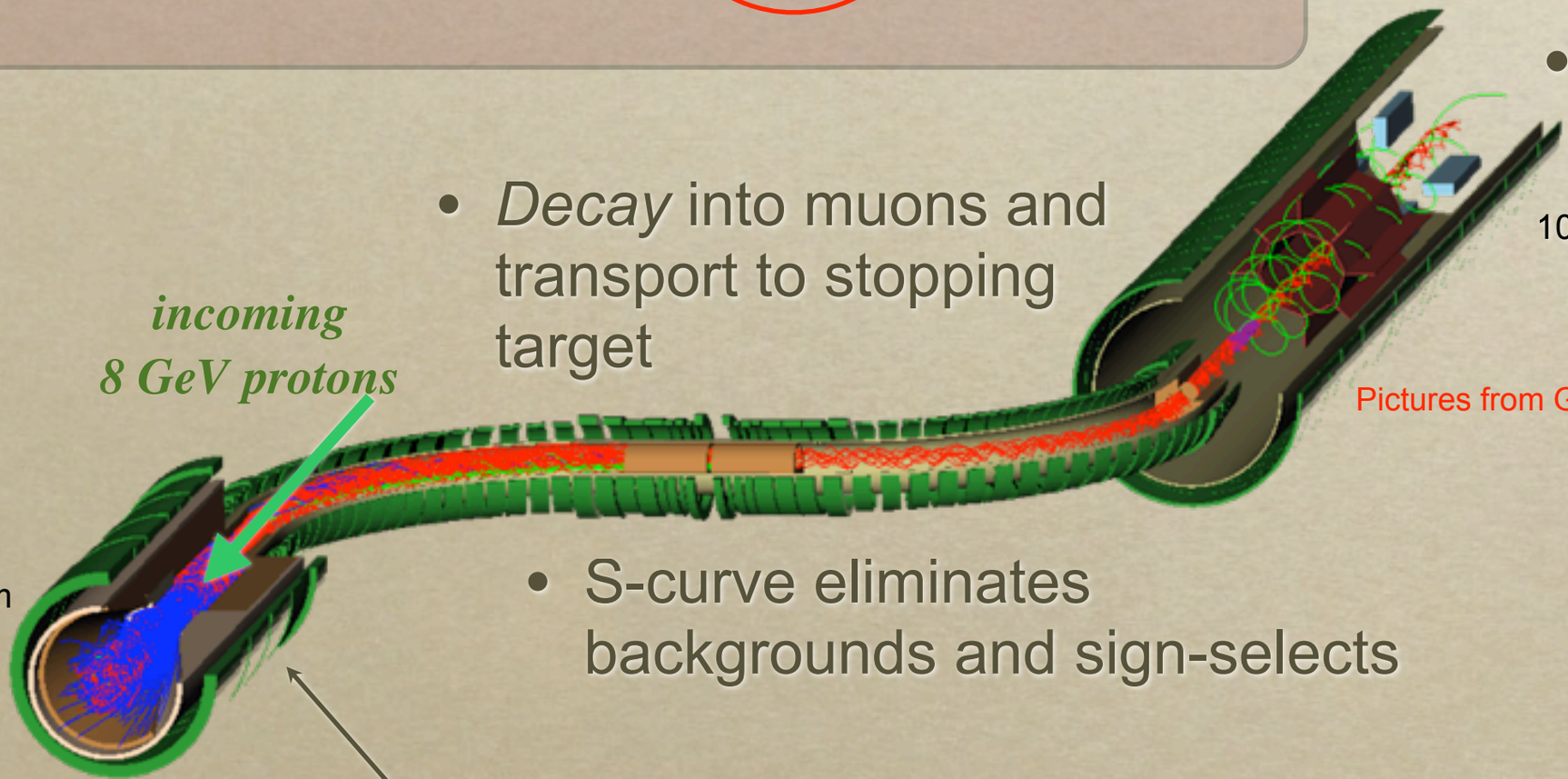
μ^- in 1s state



Al Nucleus
~4 fm

(bound lifetime is ~864 ns)

if μ converts into an e, then is "ejected" with a very specific energy (~105 MeV)



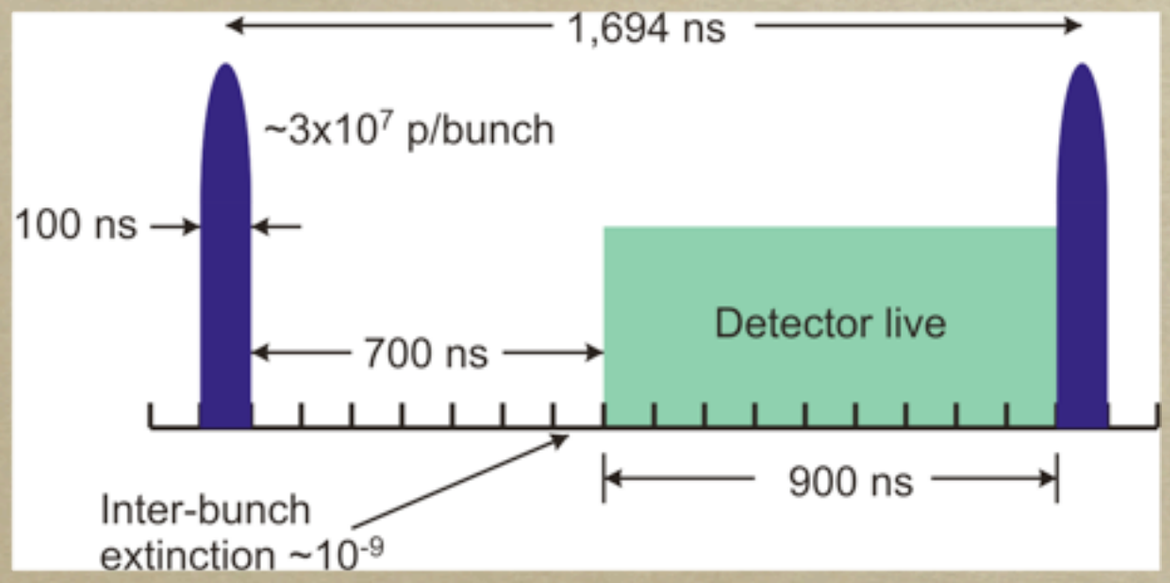
- *Tracking and Calorimeter*
- *Decay* into muons and transport to stopping target
- S-curve eliminates backgrounds and sign-selects
- *Production*: Magnetic mirror reflects π's into acceptance

Pictures from G4Beamline/MuonsInc

MJS / Fermilab

Pulsed Beam Structure for Mu2e

- Tied to prompt rate and machine: FNAL near-perfect
- Want pulse duration << τ_μ^{Al} , pulse separation ≥ τ_μ^{Al}
  - FNAL Debuncher has circumference **1.7μsec** !
- Extinction between pulses < 10^{-9} needed
  - = # protons out of pulse / # protons in pulse



- 10^{-9} based on simulation of prompt backgrounds

MJS / Fermilab

g-2 Experiment at BNL

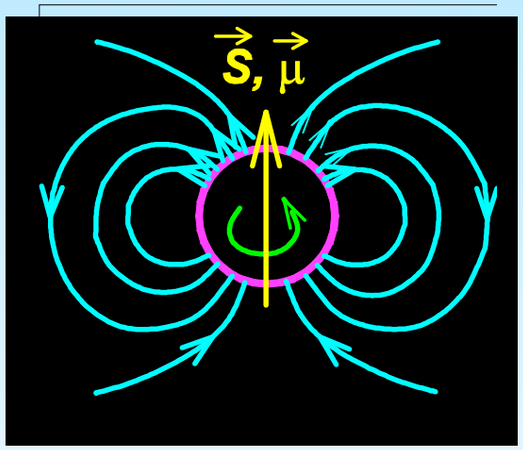
Summary of μ_s

$$\vec{\mu}_s = g_s \left(\frac{e\hbar}{2m}\right) \vec{s}$$

the moment consists of 2 parts

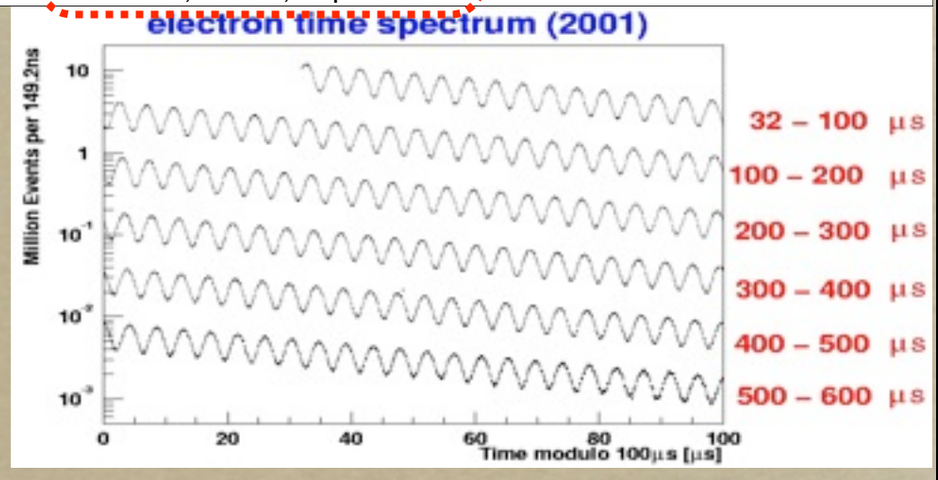
$$\mu = (1 + a)\frac{e\hbar}{2m}$$

Dirac + Pauli moment



the anomaly $a = \left(\frac{g-2}{2}\right)$; **or** $g = 2(1 + a)$

QED predicts a



MJS / Fermilab

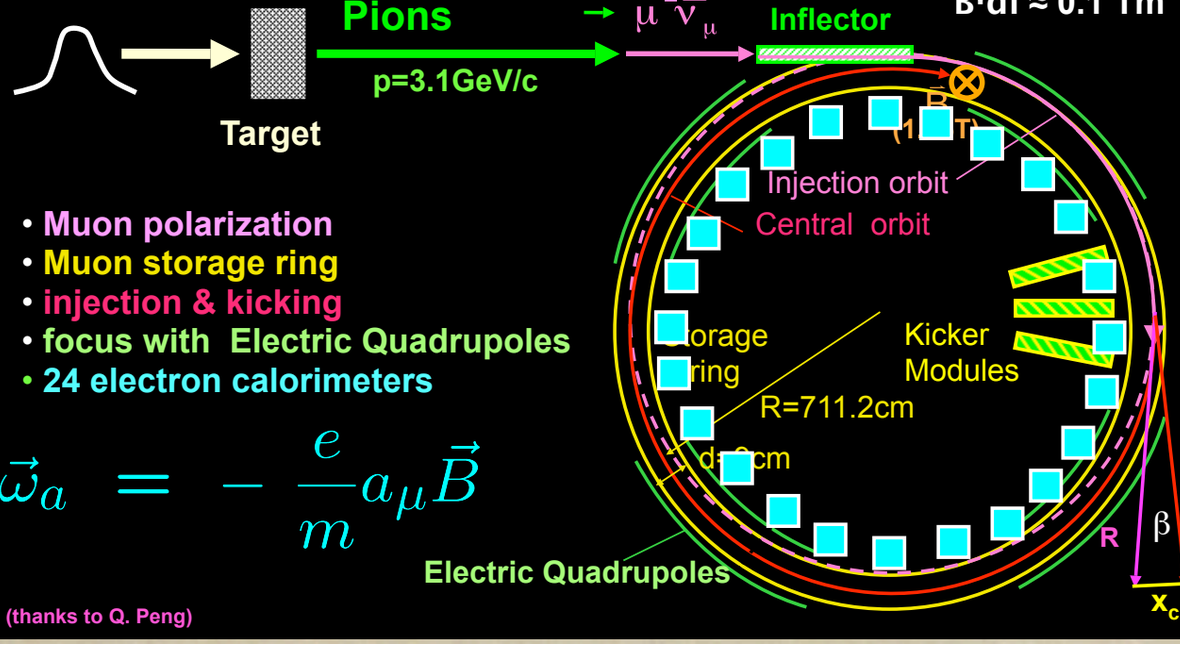
Experimental Technique

25ns bunch of
5 X 10^{12} protons
from AGS

$x_c \approx 77$ mm

$\beta \approx 10$ mrad

$B \cdot dl \approx 0.1$ Tm



- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

(thanks to Q. Peng)

g-2 Experiment at BNL

$$a_\mu = 11\,659\,208.0(6.3) \times 10^{-10}\ (0.54\ \text{ppm})$$

$$\Delta a_\mu^{(\text{today})} = (30.0 \pm 8.3) \times 10^{-10}$$

Su

$\vec{\mu}_s$

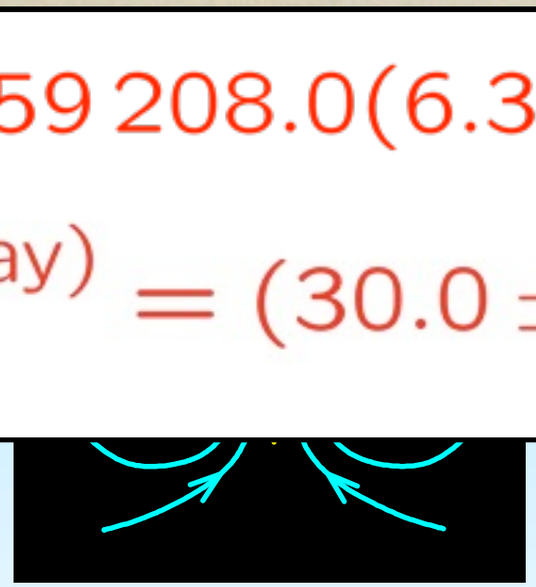
the mo

$$\mu = (1+a)\frac{}{2m}$$

Dirac + Pauli moment

the anomaly $a = \left(\frac{g-2}{2}\right)$; **or** $g = 2(1+a)$

QED predicts a



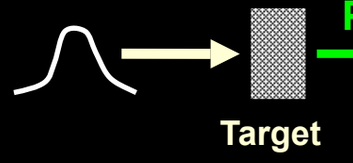
Experimental Technique

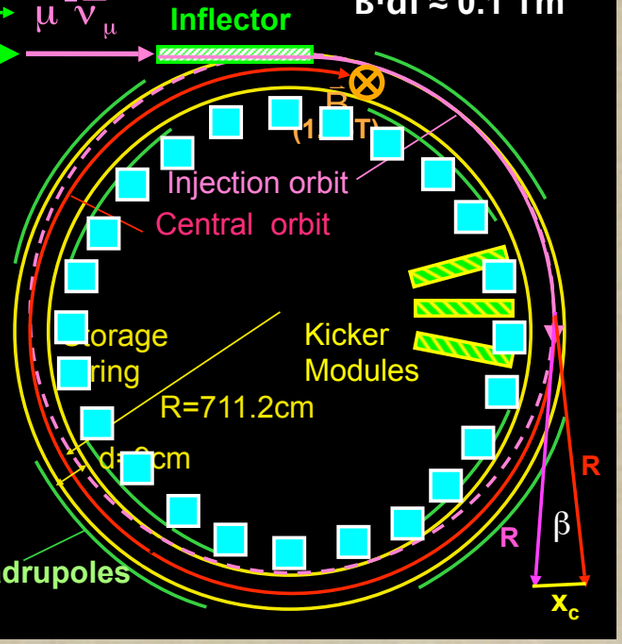
25ns bunch of
5 X 10^{12} protons
from AGS

$x_c \approx 77$ mm

$\beta \approx 10$ mrad

B·dl ≈ 0.1 Tm





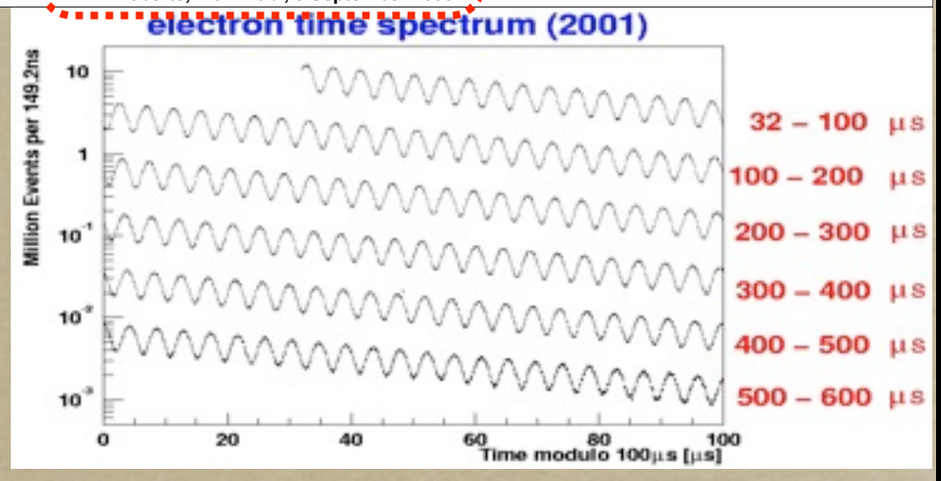
- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

(thanks to Q. Peng)

BOSTON UNIVERSITY

B. L. Roberts, Fermilab , 3 September 2008



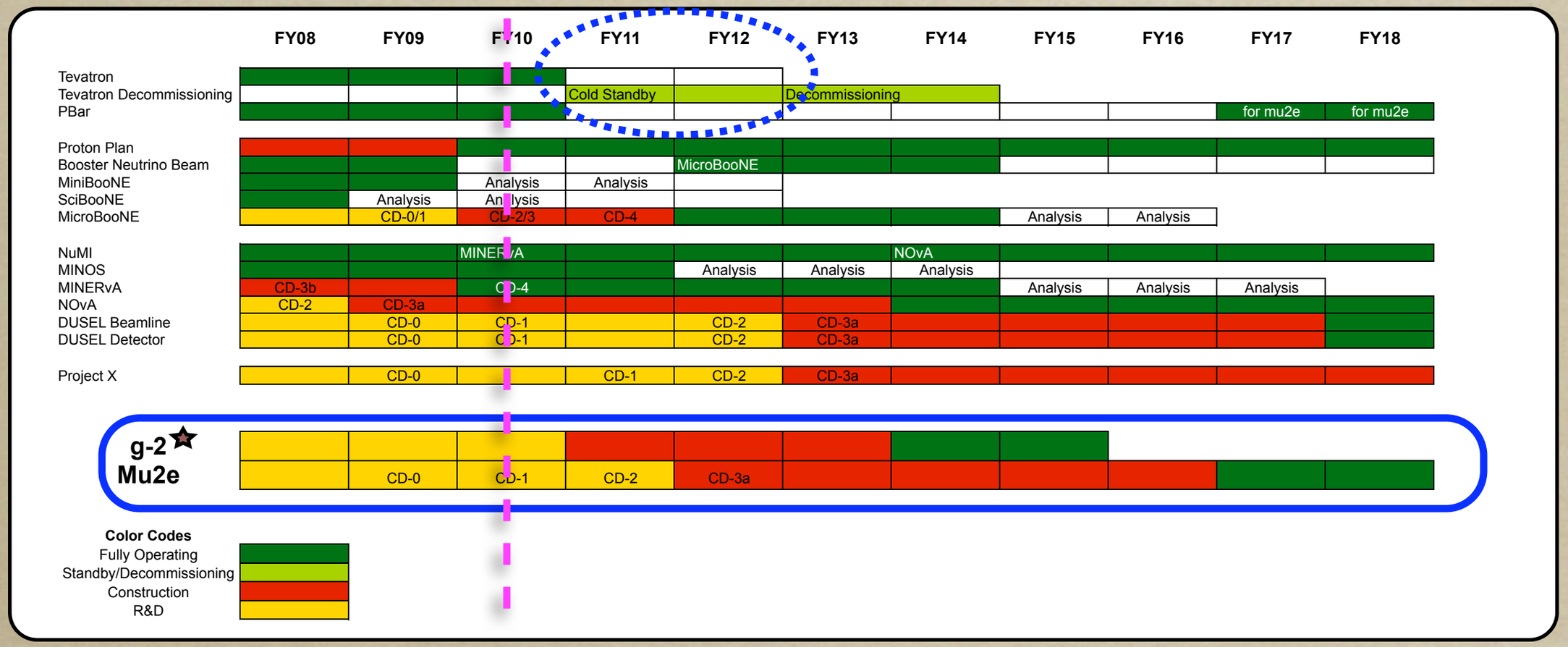
MJS / Fermilab

The New g-2 Experiment: FNAL

- *Performed at BNL, funding ran out but not the physics*
  - *3σ difference between theory / measurement seen at BNL*
- *3.09 GeV/c is "magic momentum" where the precession of the muon's spin will be purely due to magnetic fields, not electric fields; use 8.9 GeV/c proton beam infrastructure at Fermilab*
- *So, requires a special ring, with very pure dipole field -- 1 ppm*
  - *move the existing ring from BNL to Fermilab*
- *Fermilab has potential of many more protons/sec for g-2:*
  - *use "spare" Booster cycles at Fermilab injector complex*
  - *4 Tp/pulse * 6/20 pulses * 15 Hz * 10^7 s/yr = 1.8 x 10^{20}/yr*

Time Line of Events

- *While Mu2e is already* approved by the laboratory, *if New g-2 is also approved it would likely come on line first*
- *Mu2e beam scenarios were studied first, and will be presented here first*
- *Upon studying proposed operating scenarios, looking for similarities and potential overlap*



Side Note: Booster @ 15 Hz

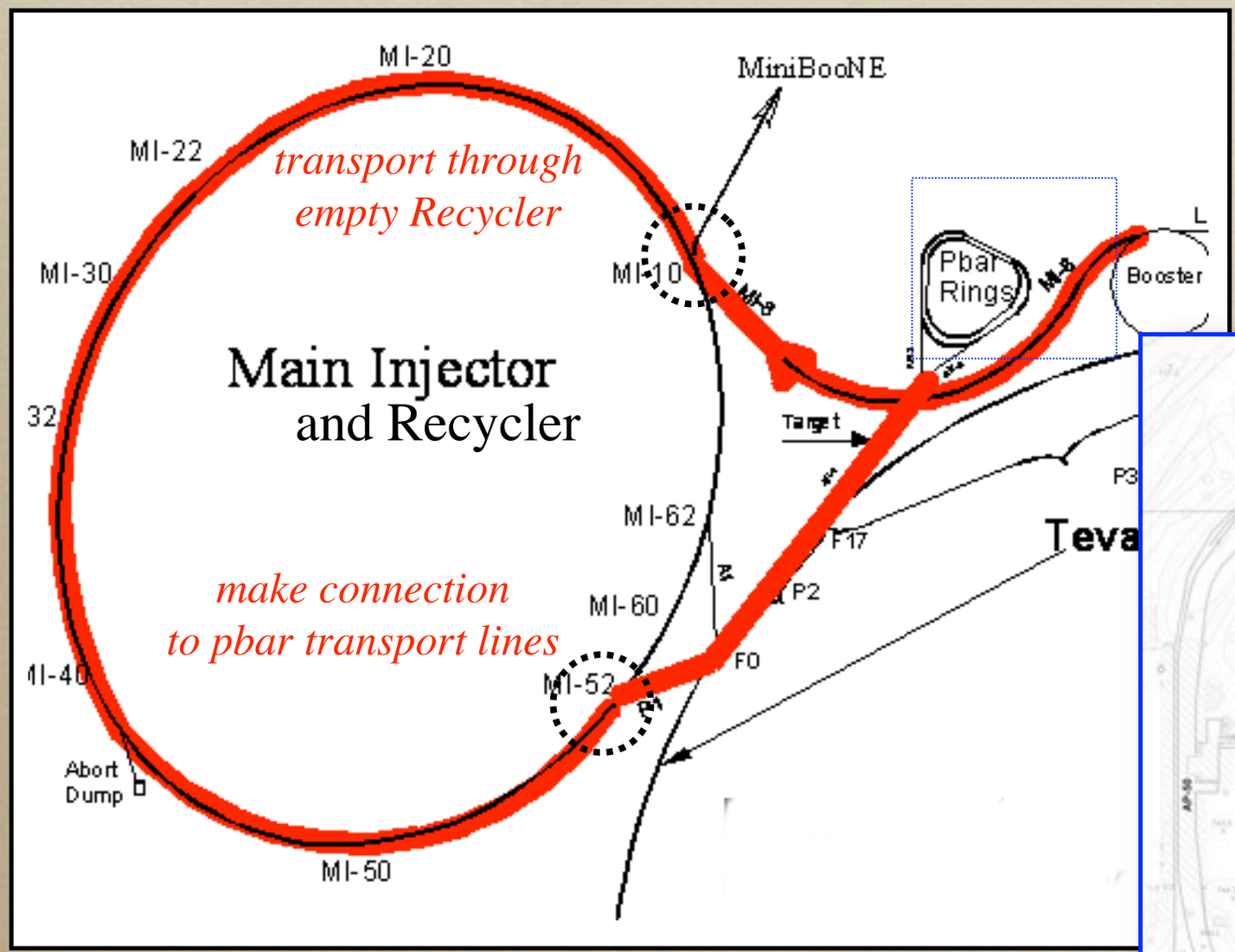
- *In order to use the remaining Booster cycles, all Booster components need to run at 15 Hz*
  - *Upgrades to Booster systems through the Proton Plan bring the repetition rate to 9-10 Hz*
  - *Further upgrades to RF systems are necessary to reach 15 Hz (other components, such as kickers, etc., can run at this level already)*
  - *In NOvA era, 15 Hz is required to run microBooNE and Mu2e (both are approved experiments); also, helps with NOvA reliability as well*
  - *15 Hz upgrades have been identified and documented; currently, not part of a particular experiment or project, but rather seen as part of overall facility improvement plans*

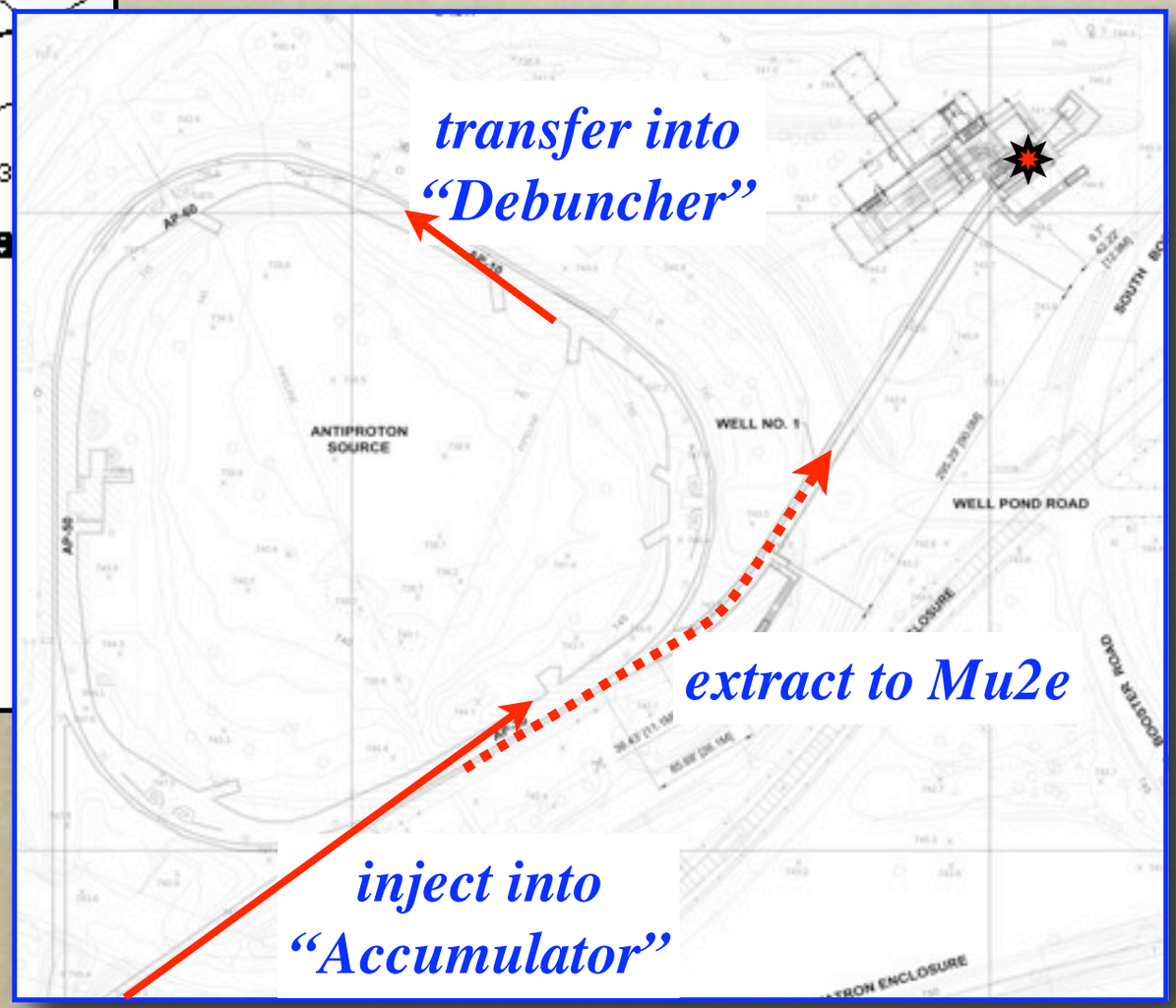
"How can *I* be a millionaire ... and never pay taxes? First, get a million dollars..." -- *Steve Martin*

Mu2e *Baseline* Beam Proposal

- *Experiment "cycle" time of 667 ms*
  - *3 Booster batches fed into Accumulator ring*
    - *form single bunch -- 1.2 x 10^{13} (!!)*
  - *transfer bunch into Debuncher ring; phase rotate to form ~30-40 ns (rms) bunch; slow extract*
- *Repeat twice during single 1.333 s NOvA cycle*
  - *NOvA uses 12/20*15 Hz cycles = 9 Hz*
  - *Mu2e would use 6/20*15 Hz cycles = 4.5 Hz*
    - *Note: 18x10^{12} p/sec (18 Tp/s) on average (25.7 kW @ 8.9 GeV)*

Beam Transport from Booster





MJS / Fermilab

Mu2e Operating Scenario: *Proposal*

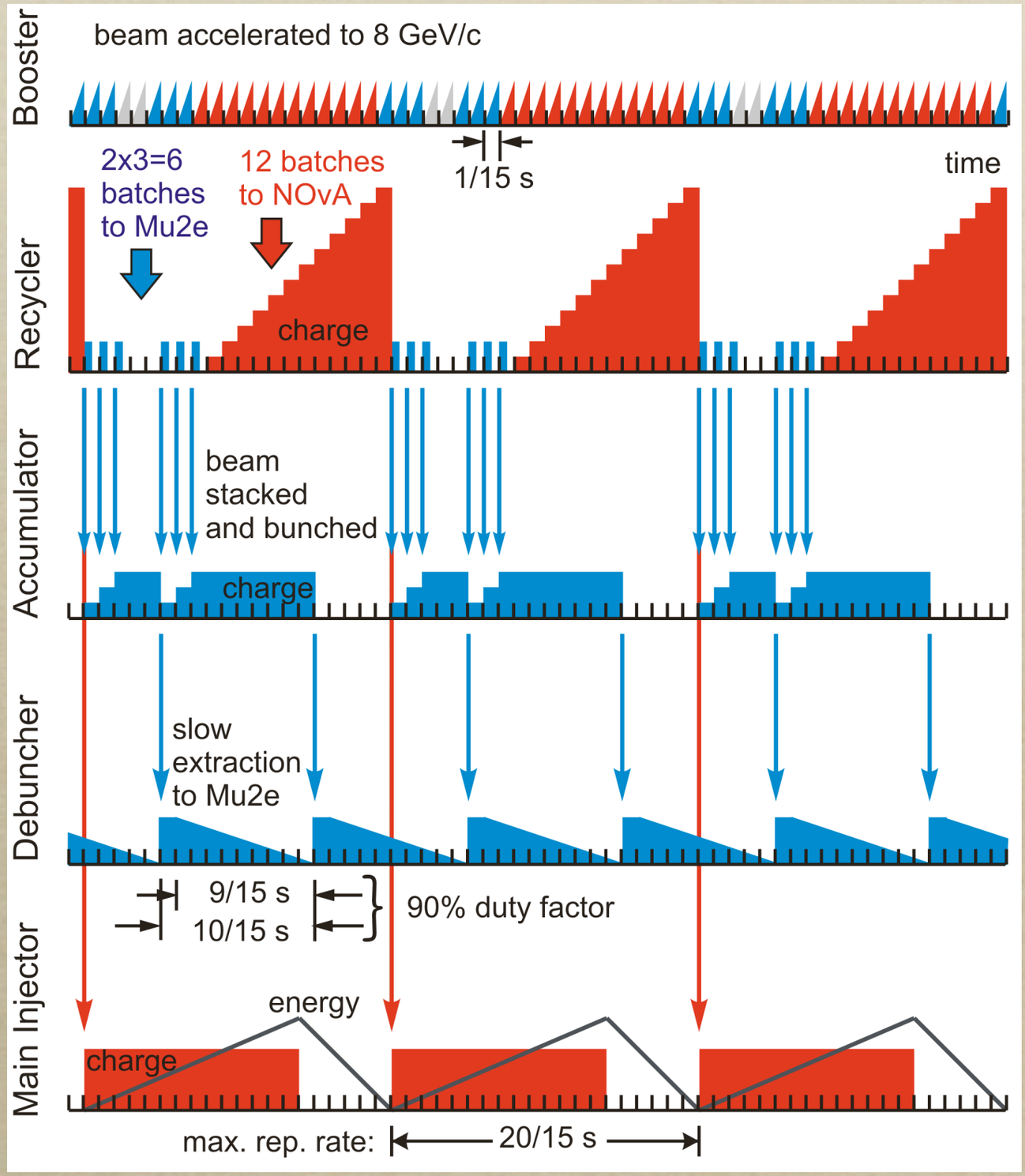
- *Inject/stack beam into Accumulator, form single bunch, and transfer to Debuncher for slow spill*

- *In principle, w/ $4x10^{12}$ (4 Tp) per Booster batch, Mu2e receives 18 Tp/s on target, $1.8x10^{20}$ in 10^{7} s.*

- *15 Hz Booster assumed*

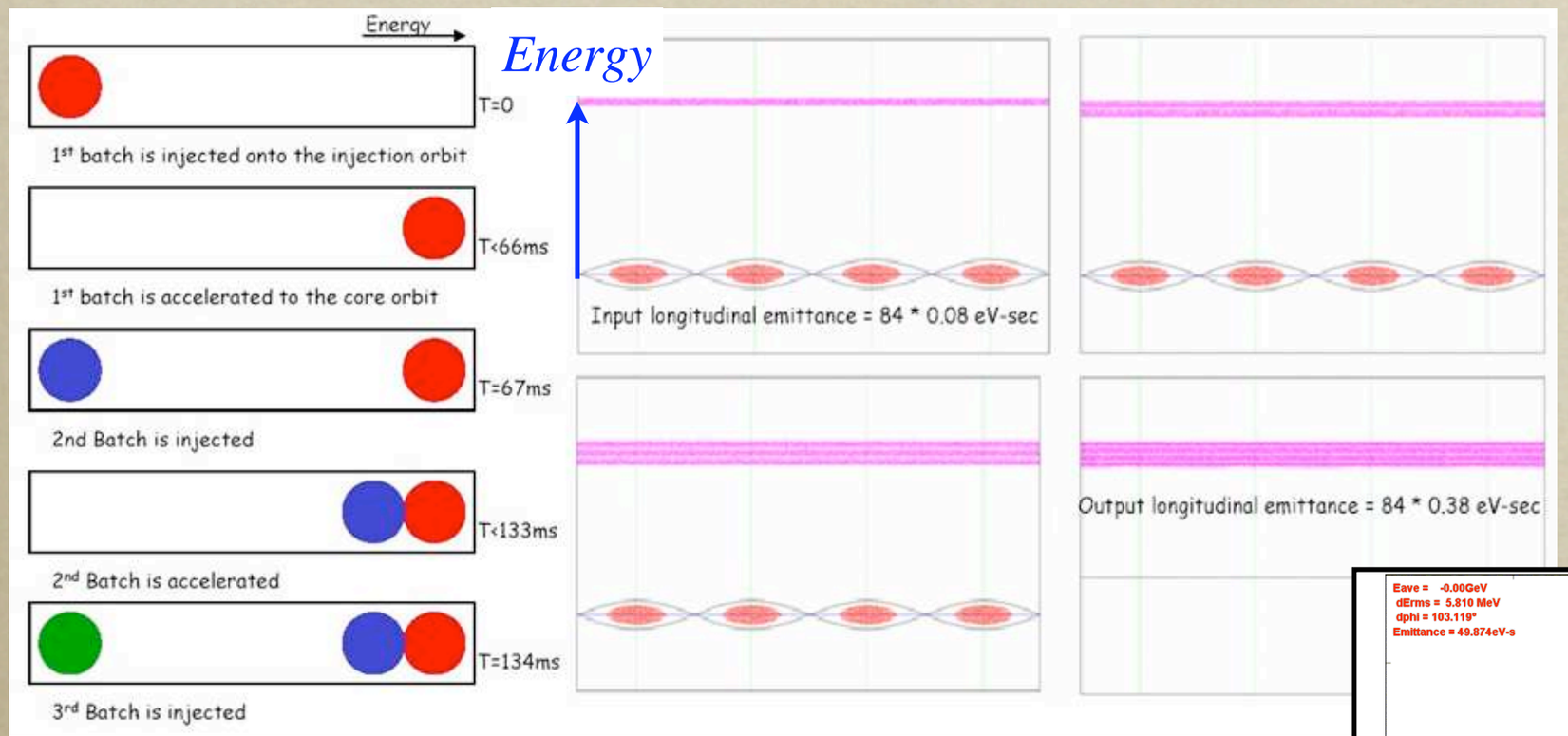
- *Does not affect NOvA operation*

- *Will require improved safety mitigation for "pbar" rings*



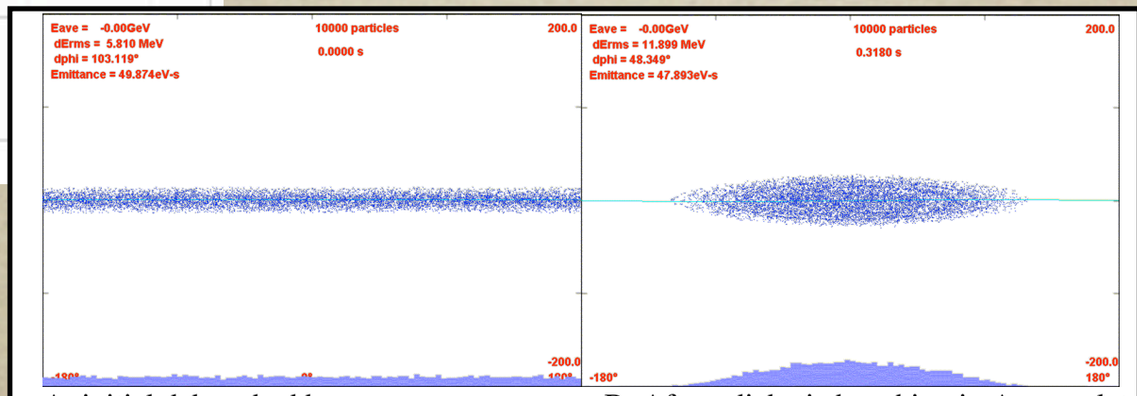
MJS / Fermilab

Bunch Formation -- Mu2e Proposal

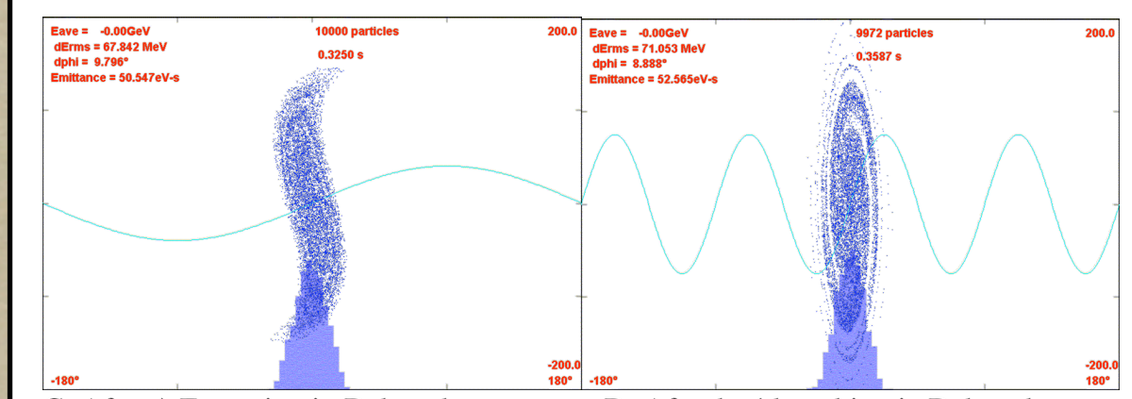


- *momentum stack in Accumulator*
- *form single bunch; x-fer to Debuncher*
- *phase rotate, re-capture*
- *40 nsec bunch, Δp/p ~ 0.8% (rms)*

MJS / Fermilab



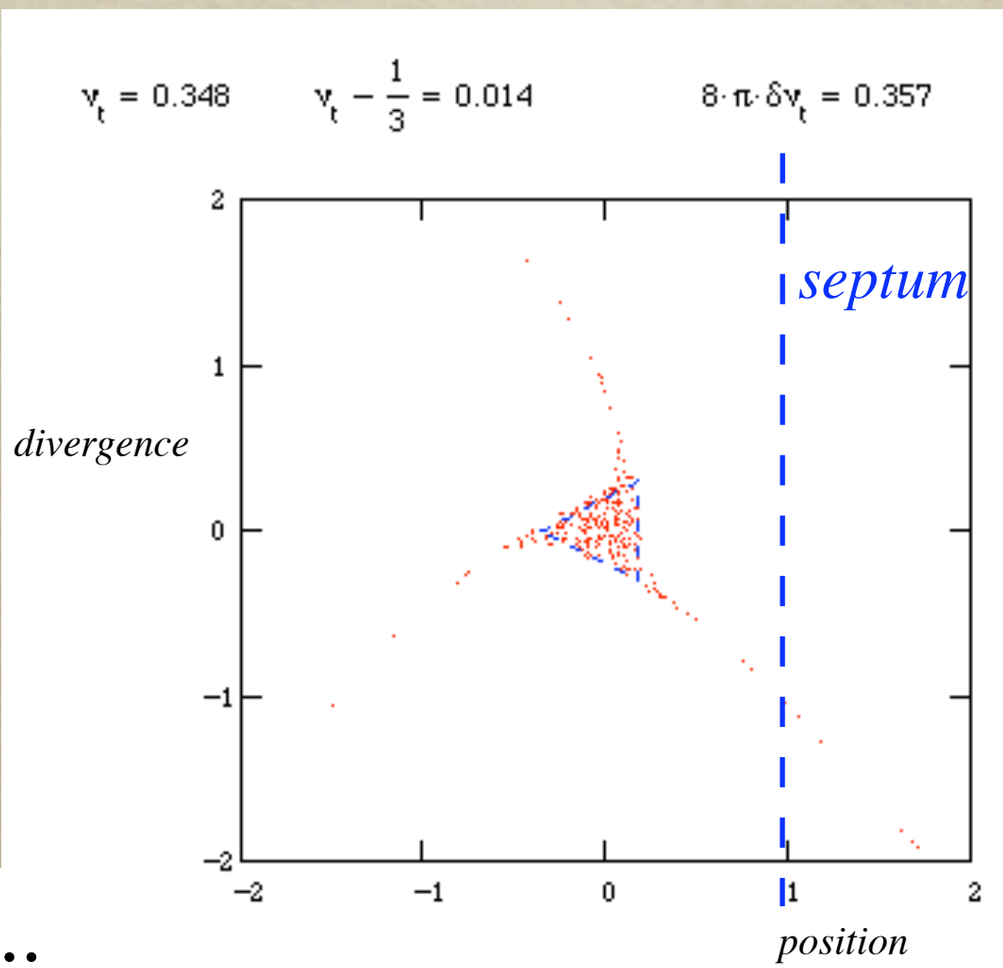
A: initial debunched beam. B: After adiabatic bunching in Accumulato



C: After ϕ-E rotation in Debuncher D: After h=4 bunching in Debuncher.

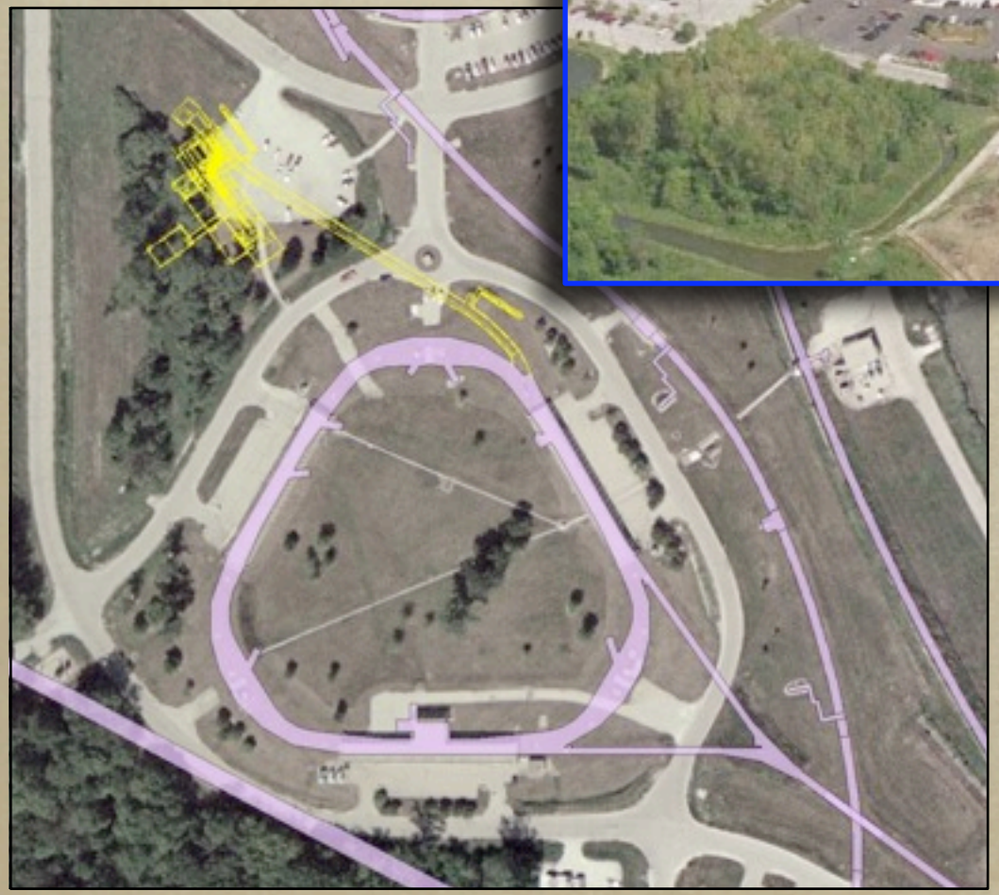
Resonant Extraction

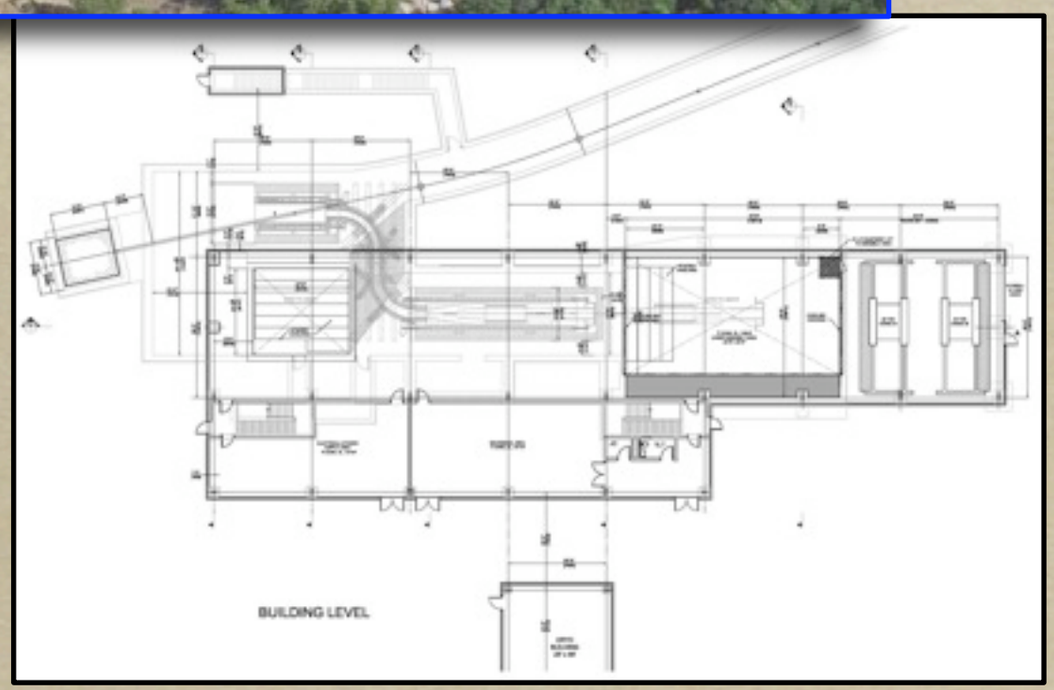
- *Once beam is in the Debuncher, "slow" spill over next 20-600 ms (depending upon scenario)*
  - *Mu2e receives ~30-50 x 10^6 protons every 1.7 μs*
- *Resonant Extraction*
  - *adjust betatron tune to be near rational value*
  - *use feedback to control rate of particle extraction*



generic example…

Experiment Location





MJS / Fermilab

Mu2e Beam Concerns

- *The beam accumulated each Mu2e cycle would be >5 times more particles than ever stored in these rings -- and would repeat every 600 ms on average!*
- *Forming a single 12 Tp bunch of 40 ns rms length introduces large space charge effects, making slow spill difficult*
- *Meeting the "extinction" level required for the experiment will be formidable task*
- *More later....*

The g-2 Baseline Proposal

- *Deliver same average rate (18 x 10^{12}/s) to target as Mu2e, also over 6 Booster cycles, every NOvA cycle* *(conservative -- could be 8 cycles)*

  - *here, though, operates "per Booster cycle"*

    - *generate 4 bunches in the Recycler -- takes about 30 ms to perform*

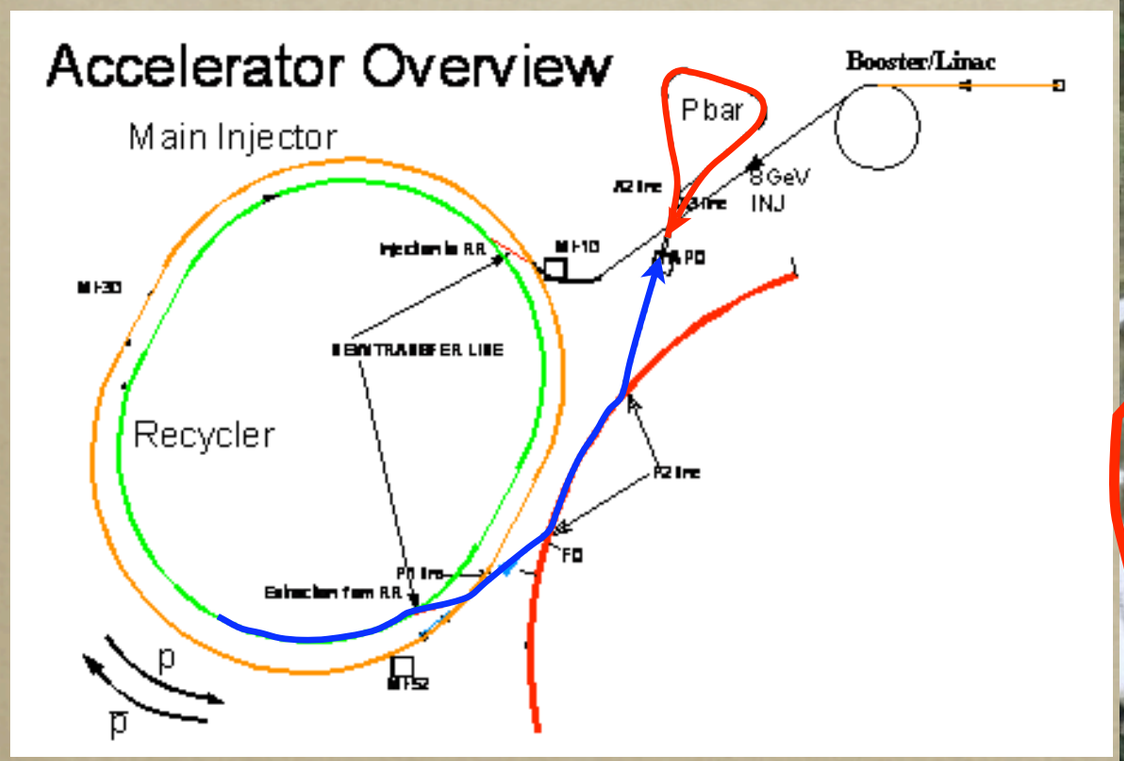
    - *transfer one-at-a-time to g-2 Ring, every 10 ms -- all within one Booster cycle*

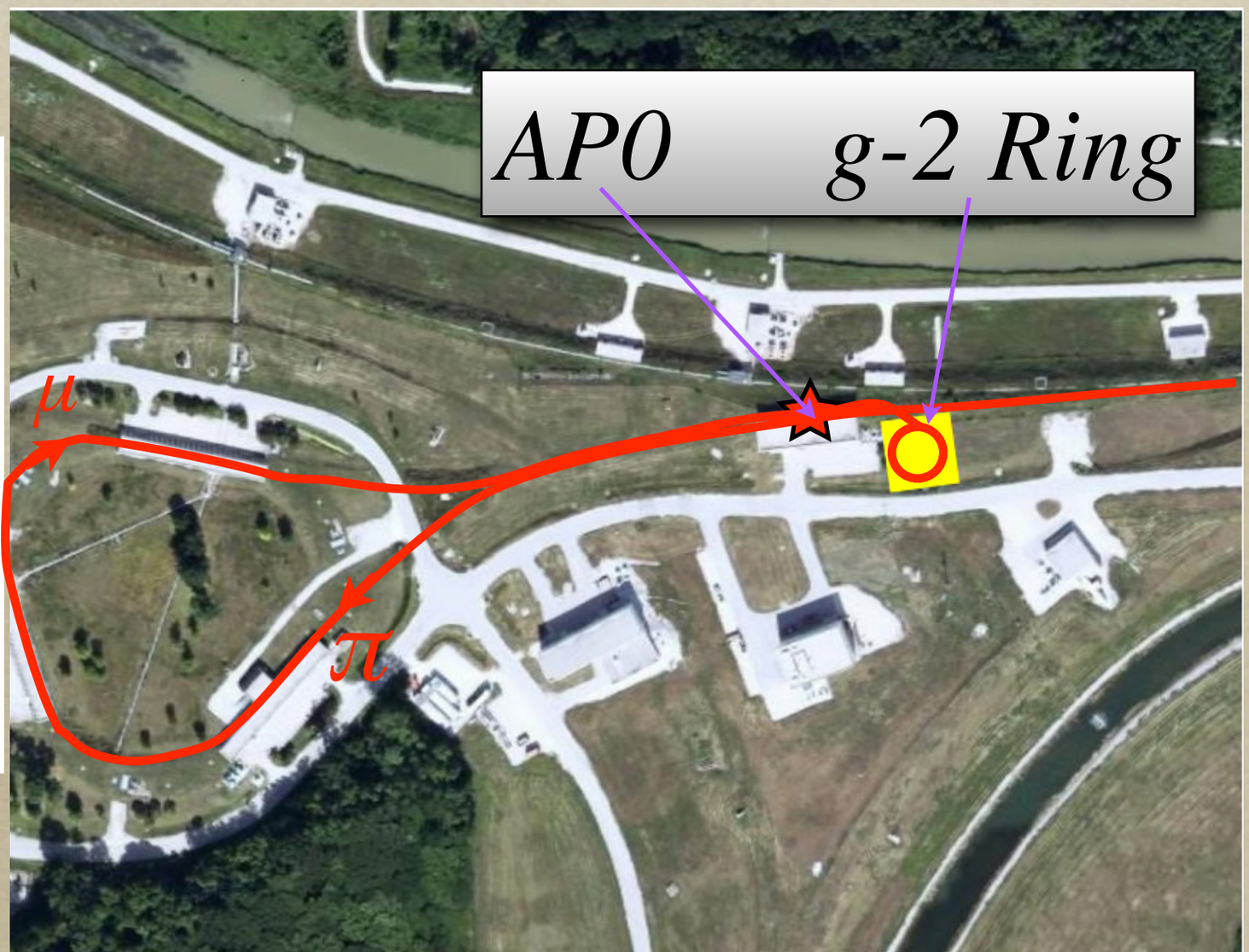
  - *Note: bunches ~30 ns (rms) in length, ~ 10^{12} each*

(similar bunch length req's as in Mu2e)

g-2 Proposed Operational Scenario

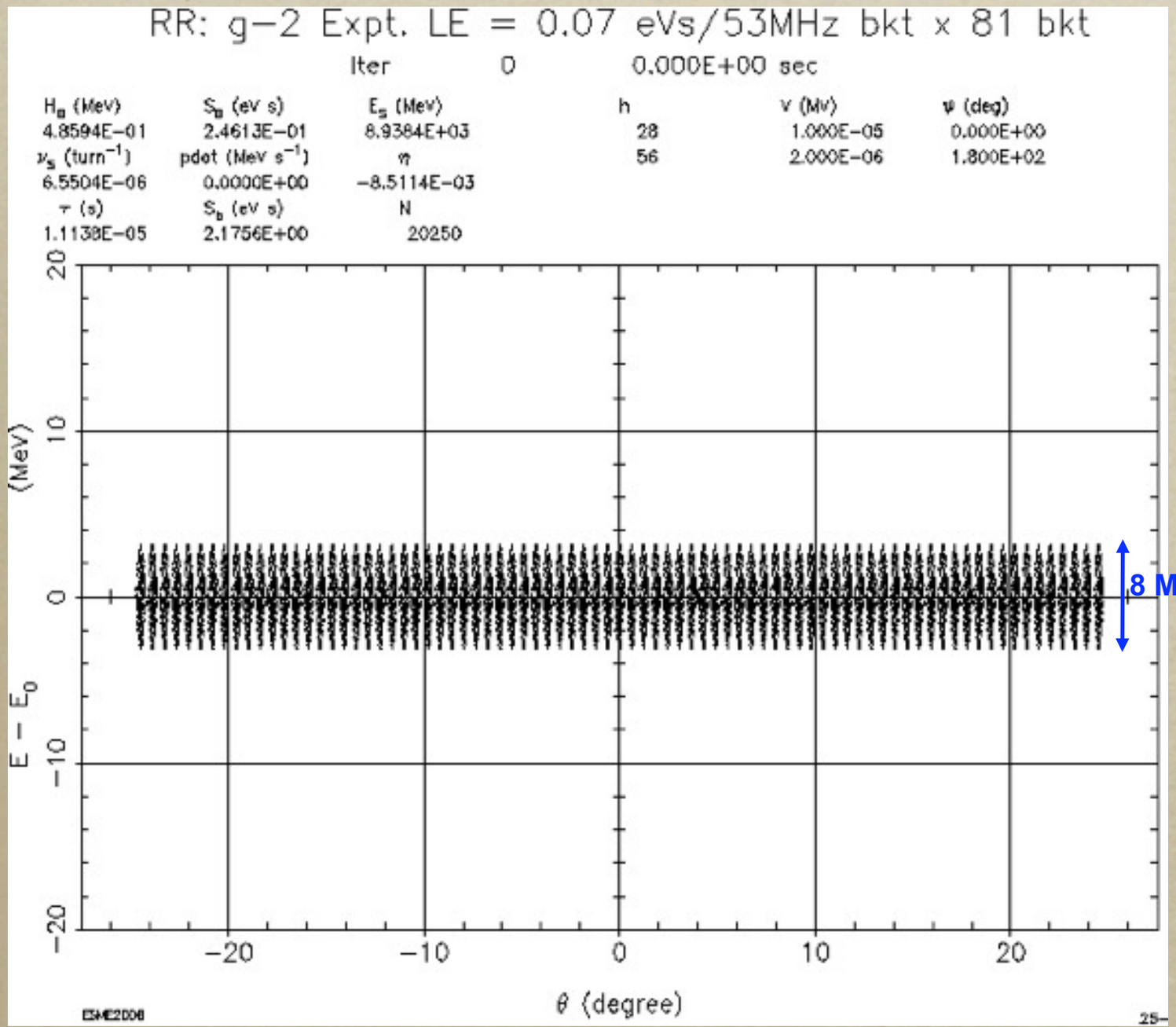
- *Generate 4 "mis-matched" bunches in Recycler that phase rotate in 24 ms; extract one every 12 ms toward pbar rings*
- *Target at AP0 target hall; use pbar rings as 1-pass "decay channel" for pions; accumulate muons in g-2 ring*

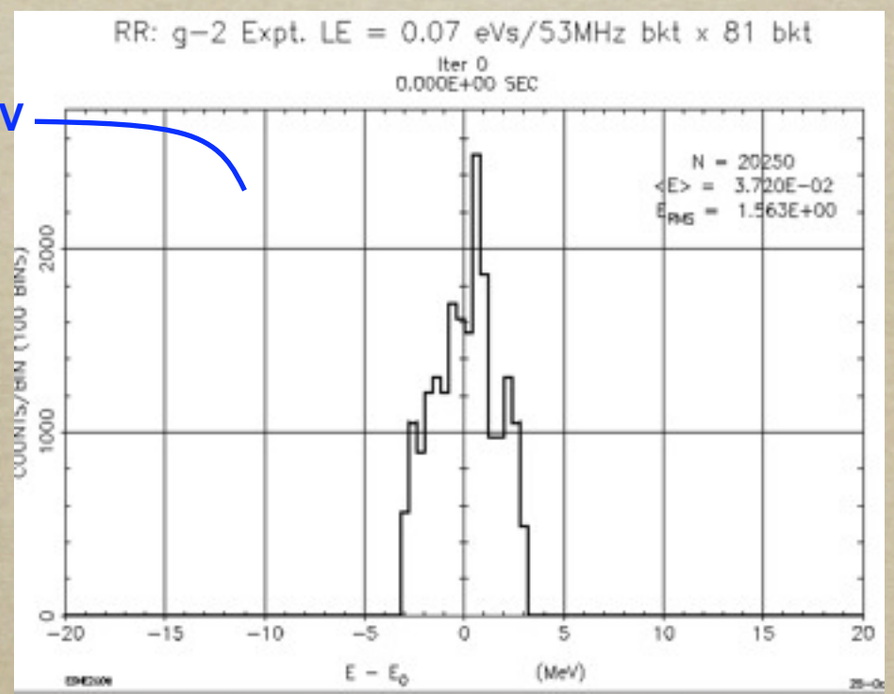




MJS / Fermilab

Simulations*





Broadband: 4 kV

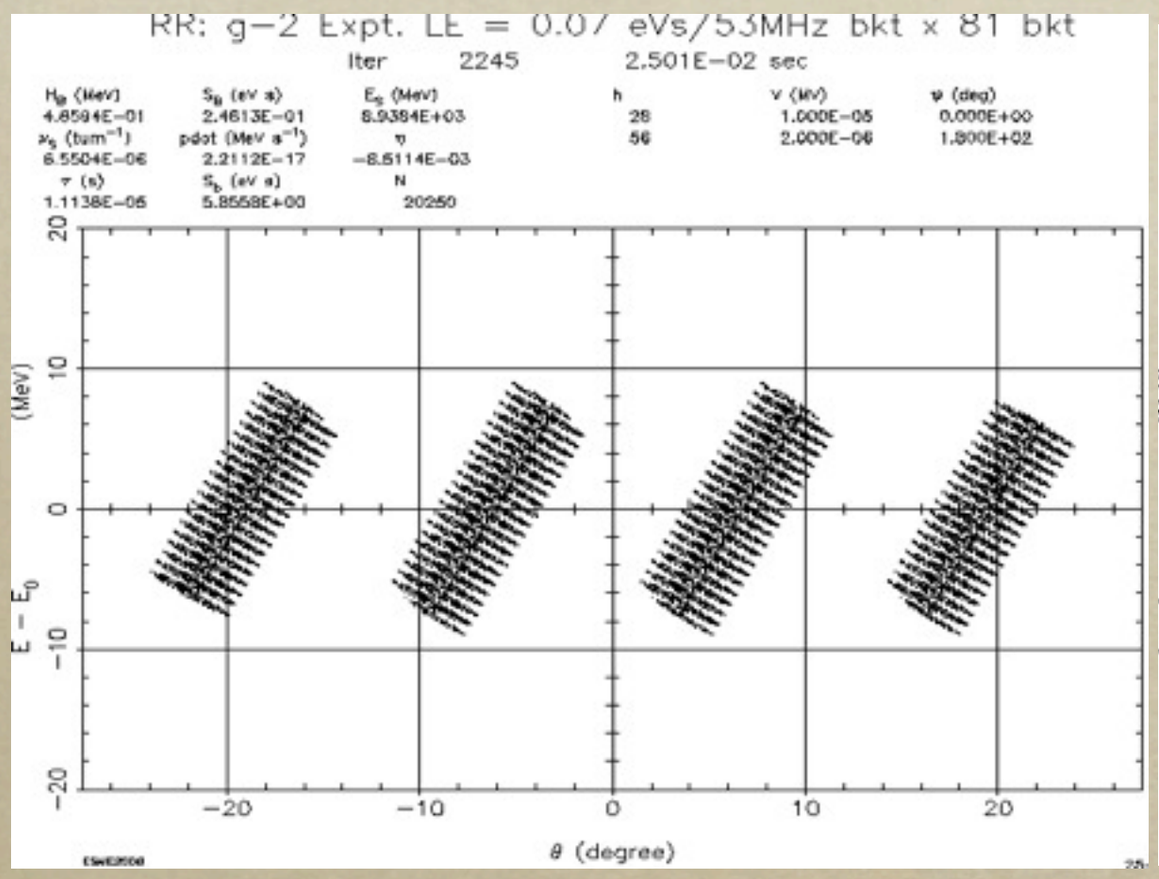
2.5 MHz: 80 kV

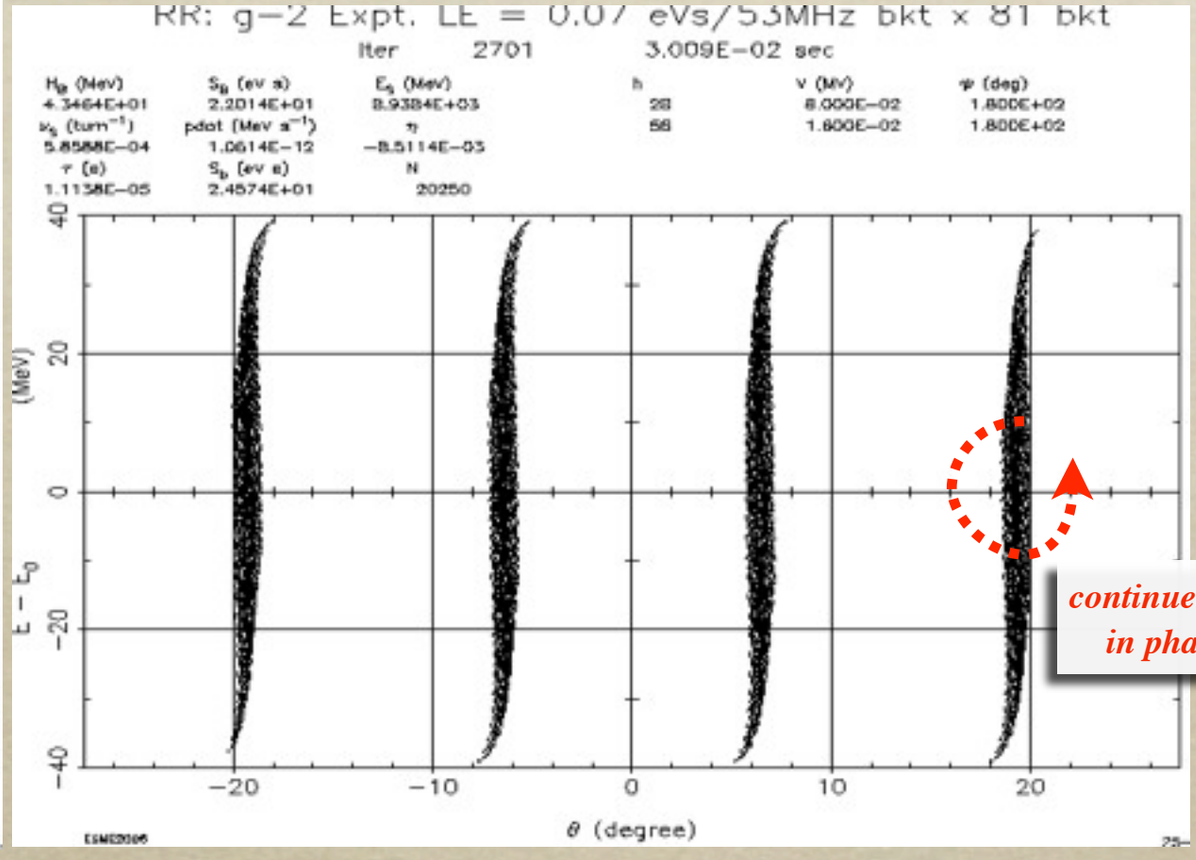
5.0 MHz: 16 kV

MJS / Fermilab

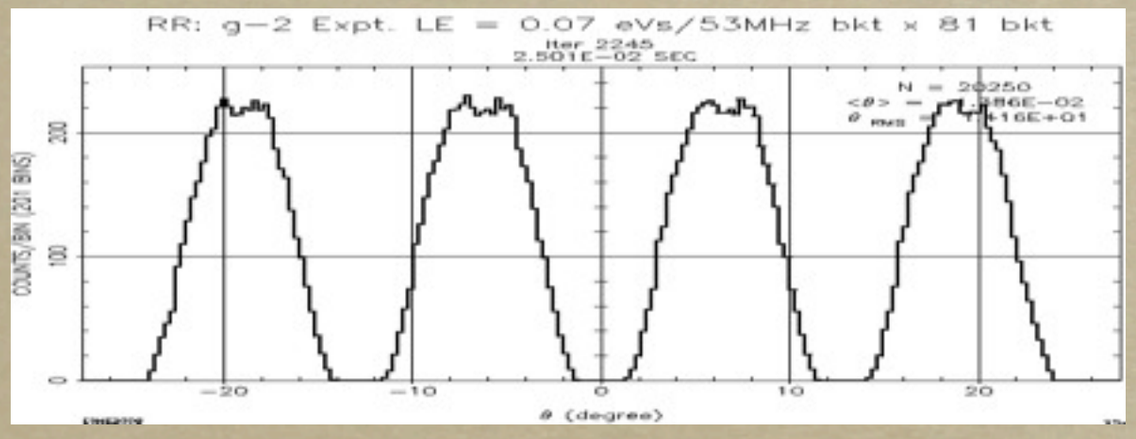
**C. Bhat and J. MacLachlan*

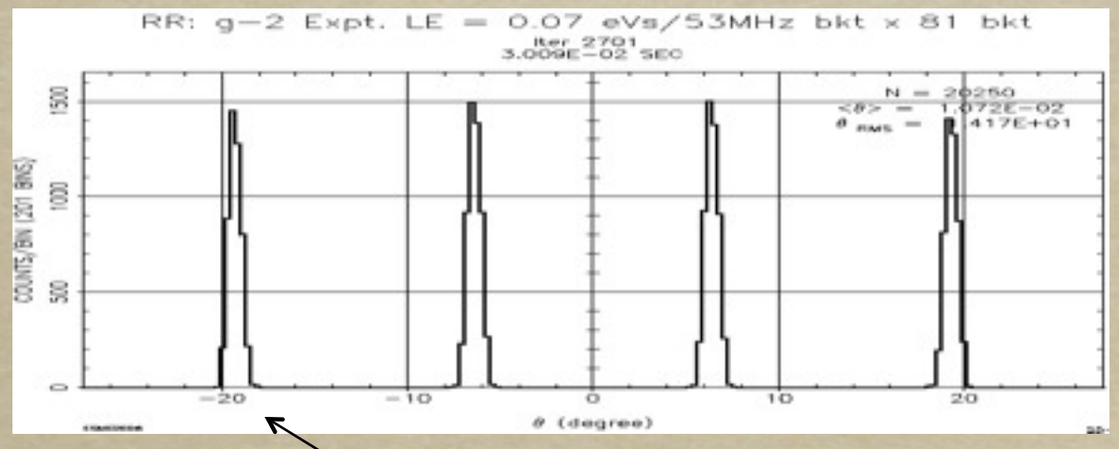
Rotate into 4 Bunches





continues to tumble in phase space

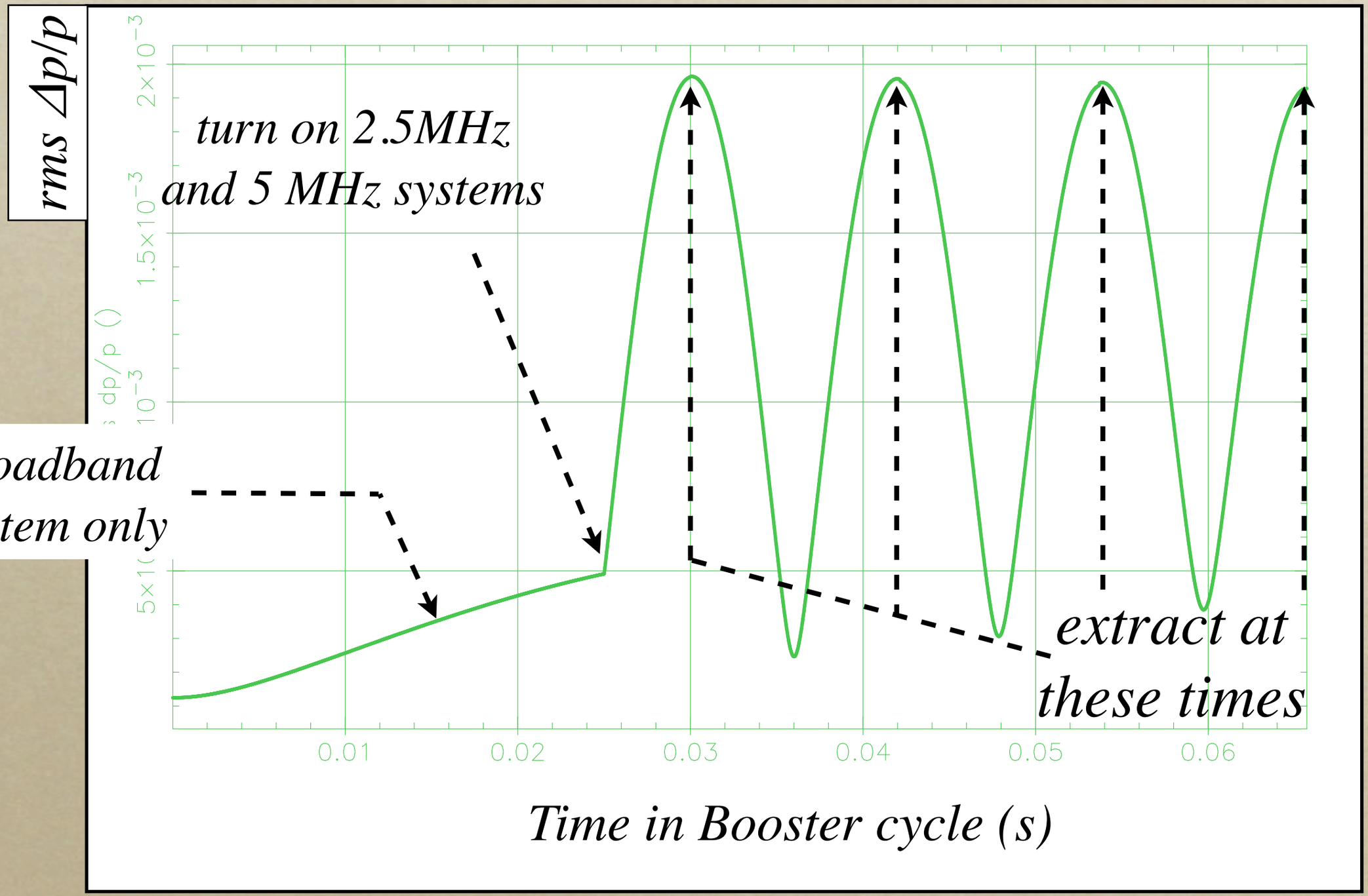




Extraction of the 1st Bunch

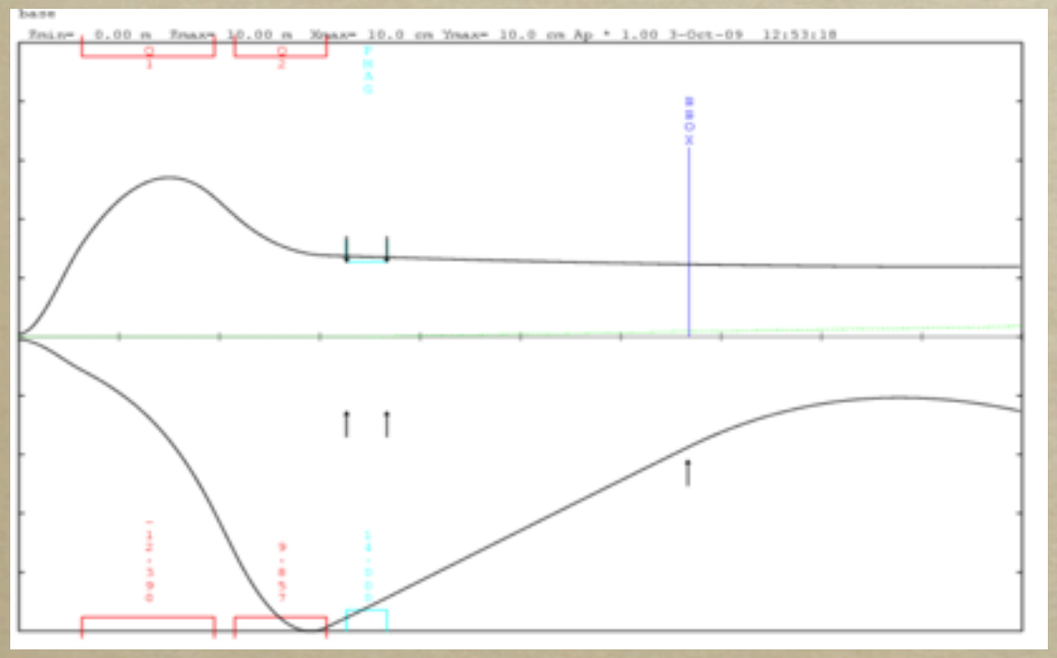
MJS / Fermilab

Momentum Spread vs. Time

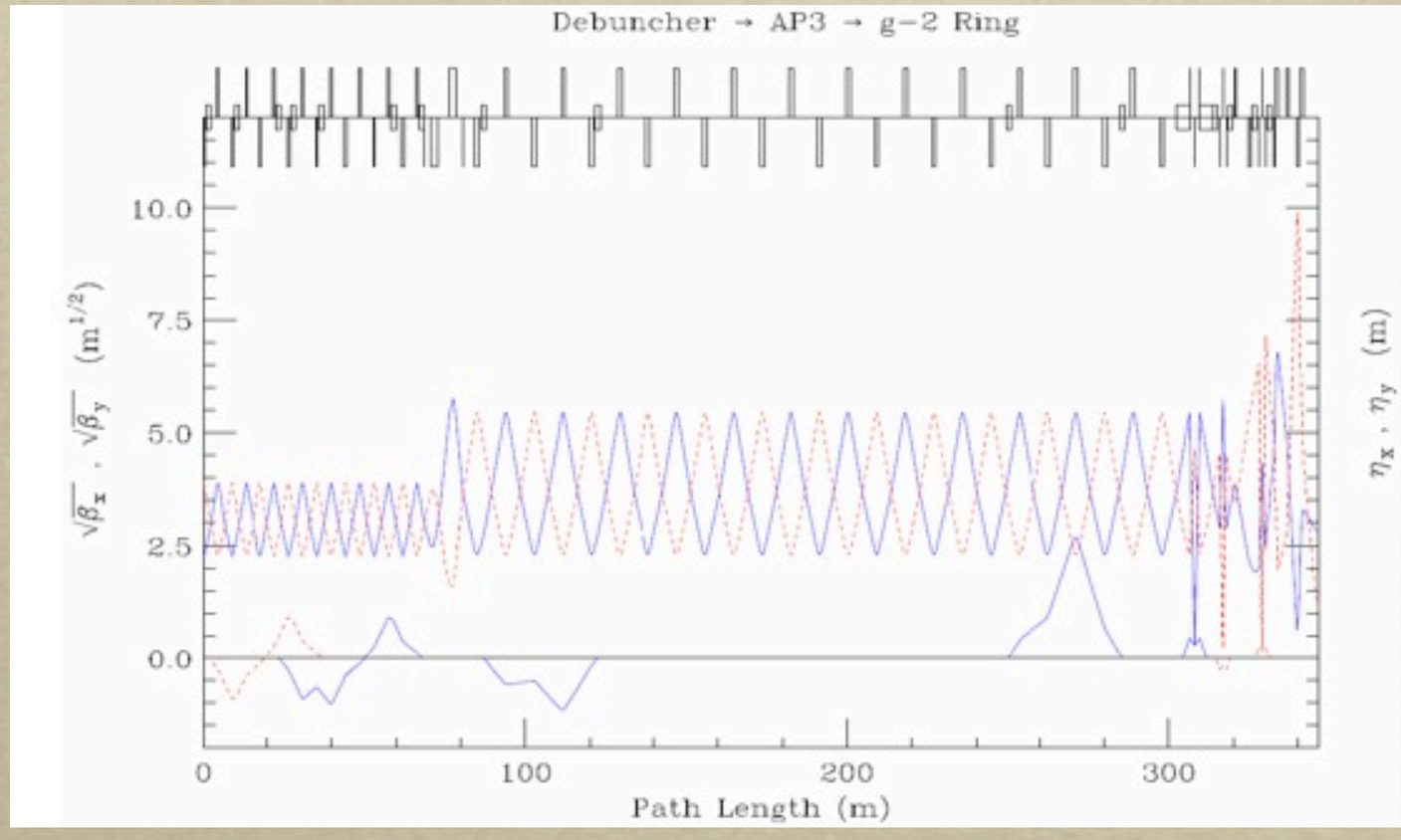


Targeting and Muon Beamline

- *Two options*
  - *Li lens, pulsed magnet to separate p and π (present p-bar targeting scheme)*
  - *rad-hard quads, static dipole magnet to separate p and π (as in beamline front end used at BNL)*



Rad-hard Q1, Q2 option

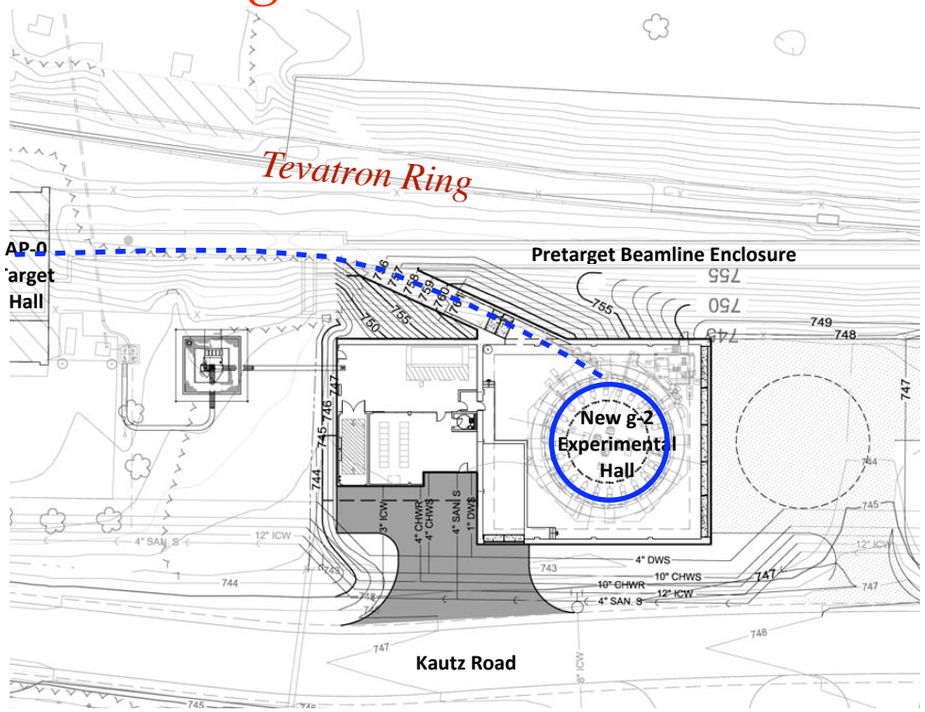


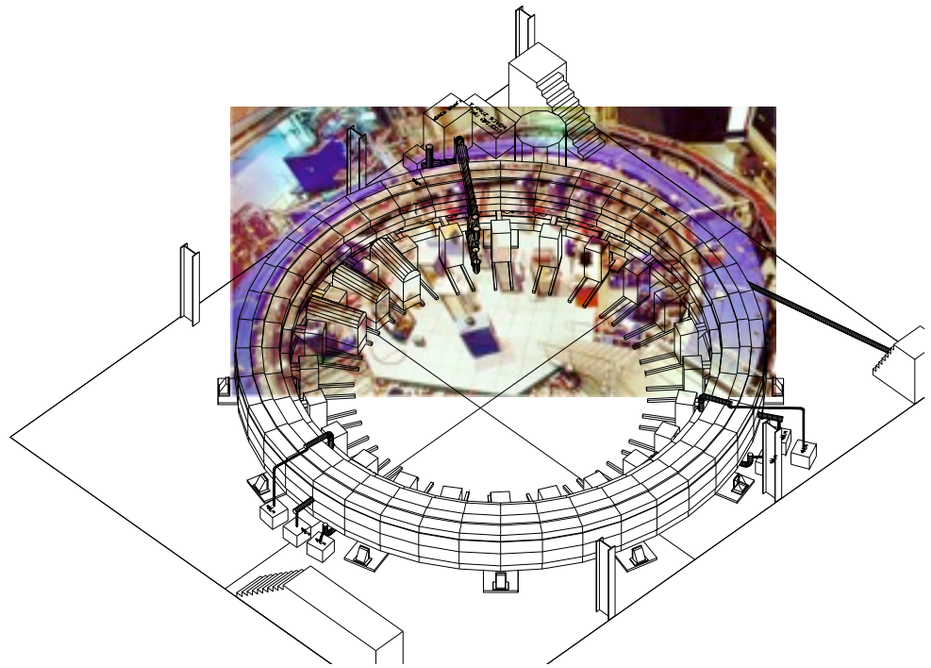
Optics of AP3 line used for costing

MJS / Fermilab

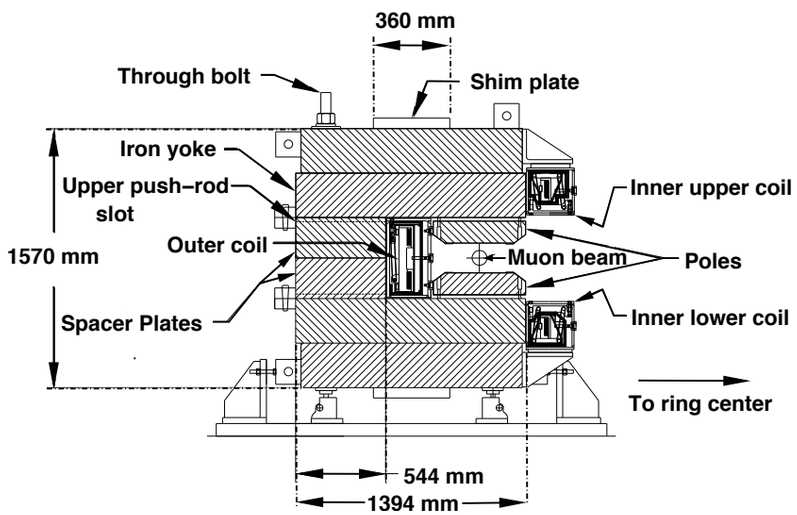
g-2 Experiment Building

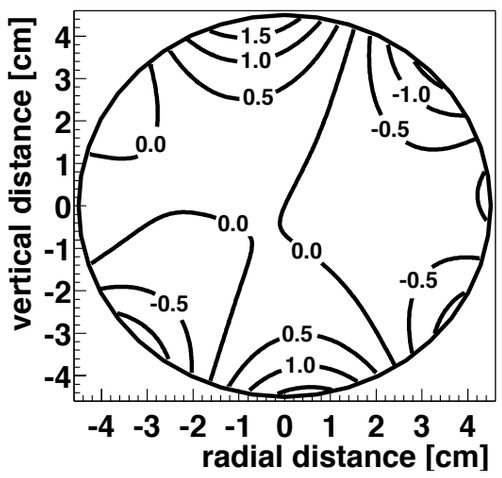
proposed siting:





- *New building*
- *New beam line from AP0 target hall*
- *E821 magnet, etc.*





MJS / Fermilab

Building Design for Fermilab from FESS

MJS / Fermilab

Can use g-2 Scheme for Mu2e?

- *Both scenarios end up with rms bunch lengths of ~20-40 ns, contained within ~2.5 MHz buckets*
- *If used g-2 "scheme" to form bunches for Mu2e, could use common RF and allow for higher throughput to the experiment*

Mu2e: High Bunch Charge

- *Space Charge will be an issue in Base scheme...*
  - *For N particles **uniformly** distributed about the ring,*

$$\Delta\nu_{s.c.} = \frac{3r_0N}{2\epsilon\gamma^2(v/c)} = \frac{3\ (1.5\times10^{-18})(1.2\times10^{13})}{2\ (20\pi\times10^{-6})(9.5^2)} \approx 0.005$$

  - *Include "bunching factor":* $\mathcal{B} \approx \frac{1700\ \text{nsec}}{40\ \text{nsec}\cdot\sqrt{2\pi}} \approx 17$

  - *Thus, expect at "design parameters":* $\Delta\nu_{s.c.} \approx 0.1$

Extraction w/ space charge

The Space Charge Effect in Slow Extraction by Third Integer Resonance

Yu.Senichev,V.Balandin
Institute for Nuclear Research of RAS,
60-th October Anniversary prosp., 7a, Moscow, 117312, Russia

EPAC94

1 INTRODUCTION

With the development and construction of high intensive beam accelerators and storage rings more and more attention is being focussed on the problem of the self-field effect of accelerated particles on the stability of their motion. This problem endures second birth, which connected with, on the one hand, requirement to know more exactly the parameters of beam and on other hand, with more powerful computers for an investigation. At first the analytical methods were used in mainly, among which the equations of Kapchinsky and Sacherer take significant place. They gave necessary information about the envelope of high intensive beam with the elliptical distribution. As far as the improvement of computer technology, the new numer-

$$\frac{e}{p_0 c} A_{sc}(x,y) - \frac{e}{p_0 c} A_{ex}(x,y), \qquad (1)$$

where A_{sc}, Φ_{sc} - the vector and the scalar potential of the space charge field and A_{ex} -the vector potential of the external field. It is assumed here, that the transverse currents are absent:

$$A_{sc} = \frac{v}{c}\Phi_{sc}(1+hx), \qquad (2)$$

where v is the longitudinal velocity equal for all particles. The vector potential of the external field has components up to the octupole inclusive:

$$-\frac{e}{cp_0} A_{ex}(x,y) = hx + (K+h^2)\frac{x^2}{2} - K\frac{y^2}{2} +$$

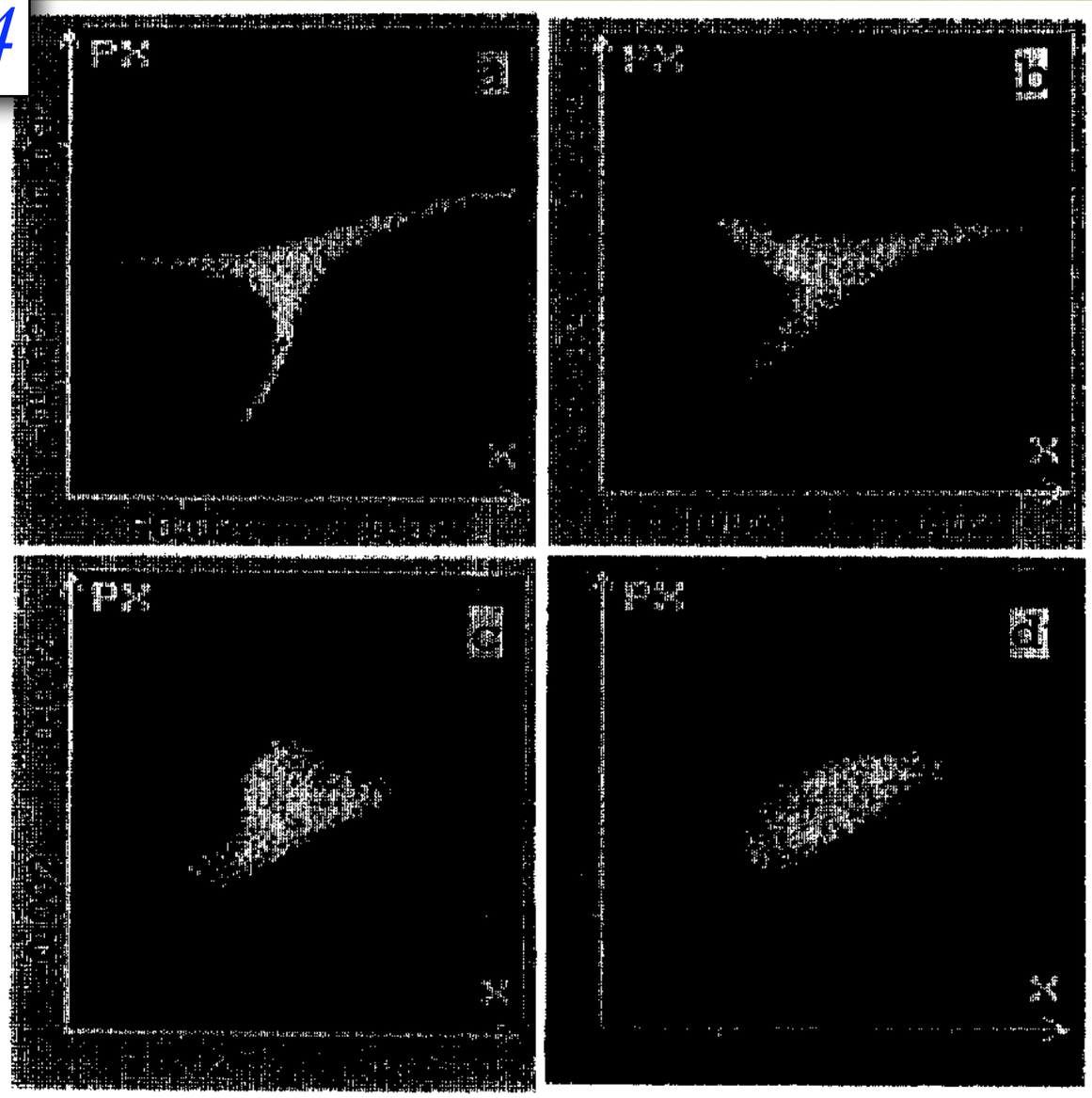


Figure 2: The phase portraits of the beam at a)$\Delta\nu_L$=0.01, b)$\Delta\nu_L$=0.03, c)$\Delta\nu_L$=0.06 and d)$\Delta\nu_L$=0.1

- *Phase space distortions in the presence of space charge, near third-integer resonance, can be very significant*

MJS / Fermilab

Early Alternate Proposal for *Mu2e*

- *Use g-2 scheme: in one Booster cycle form 4 bunches in the Recycler; transfer to Accumulator ring, transfer 1-at-a-time to the Debuncher, and slow spill over ~16 ms*
- *Each bunch is only 1 Tp, not 12 Tp*
- *Repeat each available Booster cycle*
- *May be able to utilize same or similar RF and kicker systems, etc., for both Mu2e and New g-2*
- *However, duty factor is low (<30%), and instantaneous rate is higher than desired by the Mu2e collaboration*

Early Alternate Proposal for *Mu2e*

- *Use g-2 scheme: in one Booster cycle form 4 bunches in the Recycler; transfer to Accumulator ring, transfer 1-at-a-time to the Debuncher, and slow spill over ~16 ms*
- *Each bunch is only 1 Tp, not 12 Tp*
- *Repeat each available Booster cycle*
- *May be able to utilize same or similar RF and kicker systems, etc., for both Mu2e and New g-2*
- *However, duty factor is low (<30%), and instantaneous rate is higher than desired by the Mu2e collaboration*